The relationship between large deep mafic sills, crustal contamination and the formation of Ni-(Cu) and IOCG deposits

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ABSTRACT: The Ossa Morena Zone (SW Iberia) hosts an unusual suite of ore deposits, including magmatic Ni-(Cu) and IOCG mineralization. These deposits are interpreted to have a relationship to a deep mafic sill intruded in the middle crust. Interaction of mafic magmas with crustal rocks produced immiscible sulphide-rich melts and water-rich melts. The latter exsolved large amounts of Fe- and CO_2-rich brines that were responsible for widespread albite-actinolite alteration and IOCG mineralization.

KEYWORDS: Geochemistry, Ni, Cu, Au, Fe, mafic sills

1 INTRODUCTION

In the Ossa Morena Zone (OMZ, SW Iberia), magmatic Ni-(Cu) and iron oxide-copper-gold (IOCG) deposits are contemporaneous with voluminous metaluminous calc-alkaline magmatism of Variscan age. This magmatism is related to the oblique collision between Gondwana and an exotic terrane, represented by the South Portuguese Zone, in late Devonian-Carboniferous times. Classical models suggest that most of the magmas formed overlying a subducting slab in a scheme somewhat similar to that of Pacific-like convergent margins. However, the area lacks significant volcanism and porphyry and epithermal deposits suggesting that the classical subduction-related magmatism and metallogenesis cannot be applied here.

Below the OMZ there is a deep (10-15km) seismic reflector (IRB) (Simancas *et al* 2003). It probably corresponds to a giant but discontinuous basaltic sill intruded during Variscan times along a detachment zone in the middle crust, and in which many of the structures of the area are rooted. This large intrusion probably controlled both the Variscan magmatism and ore-forming processes in the area (Tornos & Casquet 2005). This magmatic body only crops out in the southernmost OMZ (Aracena-Beja Massif, Fig. 1). Our interpretation is that the IRB controlled Variscan magmatism and hydrothermal circulation, leading to the unusual association of ore deposits.

2 GEOLOGIC SETTING AND ORE DEPOSITS

The geology of the OMZ includes a thick sequence of dark slate, quartzite and amphibolite (Serie Negra) overlain by a syn-Cadomian orogenic sequence of calc-alkaline andesite-rhyolite volcanic rocks, slate and limestone (late Neoproterozoic-early Cambrian) and limestone, slate, sandstone and alkaline-tholeiitic bimodal volcanic rocks belonging to a rift related sequence of Cambrian age. Younger sediments are scarce and are only found in the cores of synclines or in grabens. Magmatic rocks are related to both the Cadomian and Cambrian events, but the more voluminous magmatism is that related to the Variscan orogeny. These plutonic rocks occur as discrete epizonal plutons ranging in composition from ultrabasites to granite but the most common rock types by far are diorite to tonalite.

The area is rich in albite-bearing magmatic rocks. They occur as subvolcanic stocks representing the roots of the Cambrian volcanic systems but are also related to the Variscan rocks.

Variscan deformation in the OMZ is dominated by thick-skinned thrusts and large faults, all of which have an important lateral displacement suggesting that deformation took

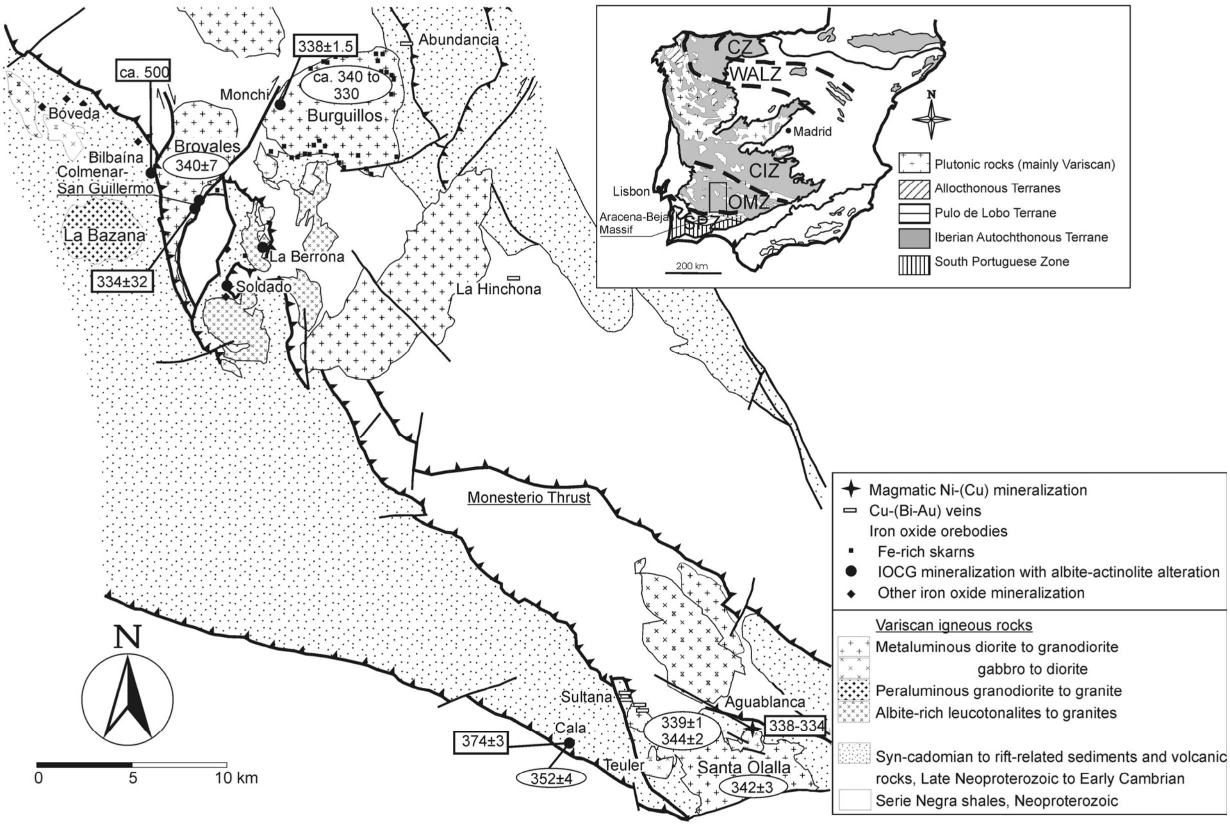

Figure 1. Geologic setting of the most significant Ni-Cu and IOCG deposits of the Ossa Morena Zone, showing the ages of individual deposits and related metaluminous plutonic rocks (in ellipses). Data from Romeo *et al.* (2006), Stein *et al.* (2006) and the compilation of Tornos & Casquet (2005). Modified from Tornos & Casquet (2005).

place in an overall left-lateral transpressive setting (Quesada 1991).

The OMZ hosts several hundreds of showings that have made it a leading producer of Pb, Zn and Fe. Nowadays, exploration is mainly focused on Ni-Cu magmatic ores and IOCG deposits.

Ni-(Cu) showings are common in both the Cadomian and Variscan plutonic rocks of the OMZ, but the most remarkable deposit is Aguablanca. This deposit is located in a subvertical, highly discontinuous, irregular body in which massive sulphides cement fragments of ultramafic rocks. This high-grade ore is surrounded by gabbro to norite with disseminated sulphide ore. Fragments in the breccia are heavily dominated by pyroxenite, and only sporadic fragments of other compositions are found. They include host rocks, skarns and some olivine-rich ultramafic rocks. This deposit is interpreted to have formed via the disruption of a deep, layered magmatic complex by injection of molten sulfides to epizonal levels, through a localized pull apart structure in the overall compressive setting (Tornos *et al* 2006). Lithogeochemistry and isotope geochemistry trace a major crustal contamination that obliterates the original juvenile values of the magmatic rocks. High $^{87}Sr/^{86}Sr$ (0.708-0.710) and low $^{143}Nd/^{144}Nd$ (0.512-0.513) values are accompanied by typical crustal signatures of $\delta^{34}S$ (7.4‰), Pb (μ, 9.6-9.8) and Os (γOs, 40-65) (Casquet *et al* 2001; Tornos & Chiaradia 2004; Mathur *et al unpub. data*).

Iron oxide deposits, although not large, are widespread in the OMZ. Some of them are exhalative in the Cambrian sequence but others ones are clearly replacive and share many features with the IOCG style of mineralization. They are replacive with respect to the late Neoproterozoic-early Cambrian synorogenic sequence, mainly interbedded calc-silicate rocks and slate; where carbonate rocks are present, they develop large calcic and magnesian skarns. As a whole, they show a vertical zonation. Deep Cu-Au-poor magnetite-rich systems (Colmenar, Berrona, Monchi) are associated with albite-actinolite alteration, and adjacent to albite-rich magmatic rocks. Shallow systems (Cala) are richer in Cu-Au, have a biotite-sericite-chlorite-ankerite alteration and are apparently unrelated to intrusions. In both cases, the mineralization shows a major tectonic control (Tornos & Casquet 2005; Carriedo *et al* 2007).

Fluid inclusion and isotope data show that fluids related with the IOCG deposits are very heterogeneous, always hypersaline and sometimes enriched in CO_2-CH_4, and underwent complex processes of unmixing-mixing. Fluids in the deep systems are characterized by relatively heavy $\delta^{18}O$ values (9-15‰) and δD (-35 to -30‰) signatures within the metamorphic field but close to magmatic values. In shallow systems they show O-D values that indicate mixing with surficial waters. However, all Nd (εNd, -8 to -4; Tornos & Casquet 2005), Pb (μ, 9.6-9.9; Tornos & Chiaradia 2004) and Os (γOs, 380; Stein *et al* 2006) isotopic values are indicative of a large crustally-derived component. Sulphur ($\delta^{34}S$, 3.6 to 20‰) is also mostly derived from the host metasedimentary sequence.

Dating of hydrothermal and magmatic rocks (in progress) shows that most of them are contemporaneous. Variscan mineralization ranges in age from *ca*. 374 to 340 Ma while magmatic rocks are near 340 Ma (342-338; see a compilation in Tornos *et al* 2005 and Romeo *et al* 2006). These ages are also equivalent to those of the mineralization at Aguablanca (Spiering *et al* 2005; Romeo *et al* 2006) and those of the deep sill (336±2 Ma; Tornos *et al* 2006). However, there is not always a direct relationship between magmatism and mineralization. For example, Re-Os dating of magnetite at the Cala orebody show that at least some of the magnetite mineralization predated by the adjacent plutonic rocks some 20 Ma (Stein *et al* 2006).

3 ORE FORMING PROCESSES IN THE OMZ

Geological and geochemical data on mineralization and related rocks in the OMZ suggest a scenario in which the intrusion of the mafic sill had a critical influence on the ore forming systems. Crustal contamination of deep mafic magmas intruded in the middle crust is responsible of the formation of both IOCG and magmatic Ni-(Cu) deposits in the OMZ. Intrusion of juvenile magmas into water-bearing low grade metamorphic slate produced widespread dehydration of the metamorphic rocks but water-enrichment in the magma was accompanied by assimilation of large amounts of host rocks.

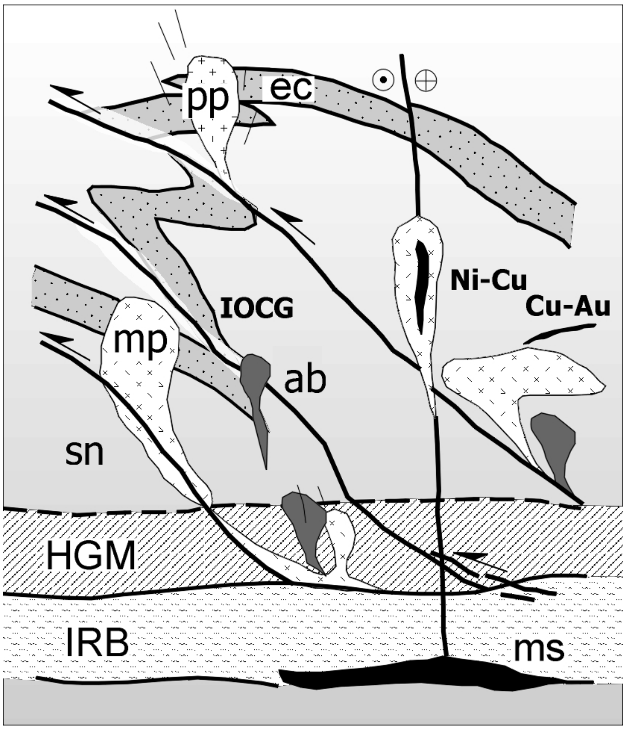

Figure 2. Sketch of the genetic relationships between metaluminous magmatism (mp), IOCG deposits and related albite-actinolite alteration (IOCG) and Ni-Cu magmatic mineralization, including both deep stratiform protore (ms) and epizonal breccias (Ni-Cu). IRB is the deep magmatic complex and HGM is the high grade metamorphic zone adjacent to the IRB. Sn is the metasedimentary Serie Negra, ec, the late Neoproterozoic-early Cambrian metasediments, pp the late Variscan peraluminous magmatism and ab, albitite. Modified from Tornos *et al.* (2005).

The contamination was so intense that geochemical signatures of mafic-intermediate rocks are controlled by those of the crustal rocks. Contamination favored the formation of sulphide-rich magmas, the protore of the Aguablanca orebody. However, it also promoted the formation of fluid-rich mafic intermediate magmas that exsolved hypersaline, iron-rich and CO_2-bearing brines. These brines were probably responsible for sodic autometasomatism and formation of albitite on igneous rocks, widespread albite-actinolite-magnetite hydrothermal alteration and related mineralization (Fig. 2).

4 CONCLUSIONS

The intrusion of the IRB controlled the metallogenic evolution of the OMZ. It inhibited the formation of intermediate, relatively dry, calc-alkaline magmas but favored the formation of highly contaminated more basic and water-rich magmas. These magmas intruded along major crustal discontinuities to shallow levels and exsolved large amounts of hypersaline, usually CO_2-bearing, brines that formed large IOCG-like hydrothermal systems. Crustal contamination also favored immiscibility of sulphide-rich magmas, which used the same channel ways as silicate melts and hydrothermal fluids to ascend to shallow levels in the crust.

Deep sills perhaps similar to those forming the IRB system can be common in transpressional settings, substantially modifying the heat flow, magmatic regime and mineralization in converging terranes. A magmatic-hydrothermal system similar to that proposed here could be important in other IOCG-rich provinces. However, the intense deformation and metamorphism that has affected Proterozoic terranes has probably masked the original relationships.

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REFERENCES

Carriedo J, Tornos F, Velasco F, Galindo C, Tornos F (2007) Complex structural and hydrothermal evolution of IOCG deposits: The Cala deposit, SW Iberia. *This volume*

Casquet C, Galindo C, Tornos F Velasco F (2001) The Aguablanca Cu-Ni ore deposit (Extremadura, Spain), a case of synorogenic orthomagmatic mineralization: Isotope composition of magmas (Sr, Nd) and ore (S). *Ore Geology Reviews* 18: 237-250.

Romeo I, Lunar R, Capote R, Quesada C, Dunning GR, Piña R, Ortega L (2006) U-Pb age constraints on Variscan magmatism and Ni-Cu-PGE metallogeny in the Ossa Morena Zone (NW Iberia). *Journal Geological Society London* 163: 837-846.

Simancas JF, Carbonell R, Gonzalez Lodeiro F, Perez Estaun A, Juhlin C, Ayarza P, Kashubin A, Azor A, Martínez Poyatos D, Ruiz Almodovar G, Pascual E, Saez R, Expósito I (2003) Crustal structure of the transpressional Variscan orogen of SW Iberia: SW Iberia deep seismic reflection profile (IBERSEIS). *Tectonics* 22: 1962-1974.

Quesada C (1991) Geological constraints on the Paleozoic tectonic evolution of tectonostratigraphic terranes in the Iberian Massif. *Tectonophysics* 185: 225-245.

Spiering ED, Rodriguez Pevida L, Castelo JM, Garcia Nieto J, Martinez Chaparro C (2005) Aguablanca: a new nickel mine in a potential new Ni/Cu and IOCG belt of southern Spain and Portugal. *Geological Society of Nevada Symposium 2005:* Window to the World: Reno, Nevada.

Stein H, Markey R, Carriedo J., Tornos F. (2006) Re-Os evidence for the origin of Fe-oxide-(Cu-Au) deposits in SW Iberia at the Frasnian-Famennian boundary. *Geochimica Cosmochimica Acta - Goldschmidt Conference Abstracts* 2006, 18: A612.

Tornos F, Casquet C (2005) A new scenario for related IOCG and Ni-(Cu) mineralisation: the relationship with giant mid-crustal mafic intrusion, Variscan Iberian Massif. *Terra Nova* 17: 286-290.

Tornos F, Chiaradia M (2004) Plumbotectonic evolution of the Ossa Morena Zone (Iberian Peninsula): Tracing the influence of mantle-crust interaction in ore forming processes. *Economic Geology*: 99: 965-985.

Tornos F, Galindo C, Casquet C, Rodríguez Pevida L, Martínez C, Martínez E, Velasco F, Iriondo A (2006) The Aguablanca Ni-(Cu) magmatic deposit (SW Spain). Geologic and geochemical controls and the relationship with deep magmatic layered complexes. *Mineralium Deposita* 41: 737-769.